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Optical wavelength modulation in free electron lasers

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At saturation the free electron laser (FEL) operates with strong optical fields in the resonator. In sufficiently strong optical fields, the electrons become trapped in deep potential wells created by the combination of the optical and undulator fields. Electrons trapped near the bottom of the potential wells oscillate at the synchrotron frequency given by $\nu_s = \sqrt{|a|}$, where a is the dimensionless field amplitude [1]. These oscillations mix with the optical wave causing sidebands at the synchrotron frequency and modulation of the optical wave envelope giving rise to the trapped particle instability. This instability causes oscillations of the power output which may be undesirable for certain applications, or in fact, useful in some specific applications.

As the optical pulse travels down the undulator, it overtakes the electron pulse by the slippage distance, $N\lambda$, where N is the number of undulator periods and λ is the optical wavelength [1]. As the electron pulse slips back relative to the optical pulse, the electrons continue to radiate coherently. This causes most of the amplification to occur in the rear of the optical pulse so that the centroid of the optical pulse moves at a speed slightly less than c. In order to ensure that a sequence of electron pulses and the stored optical pulse both start at the beginning of the undulator, the path of the optical pulse is decreased by a small amount known as the "desynchronism", $d = 2\Delta S/N\lambda$, where ΔS is the decreased distance between the mirrors. This results in a steady-state where the centroid of the optical pulse remains stationary with respect to the centroid of the electron pulse. However, features in the optical pulse may continue to evolve. When saturation occurs, the optical pulse is modulated by the synchrotron oscillations. As a result optical subpulses are created in the rear of the main optical pulse. On subsequent passes these subpulses grow and move forward relative to the optical pulse centroid. Each subpulse continues to move forward over many passes until it reaches the forward part of the optical pulse where there is no gain, and then it decreases in amplitude. The optical amplitude oscillates as the train of subpulses moves through the main pulse. This results in oscillations of the optical power even though all operational parameters remain constant. This effect is known as the "limit cycle" behavior, and was first predicted in 1982 [2] and first observed in 1993 [3].

The size, frequency, and characteristics of these oscillations are dependent on certain dimensionless parameters of the FEL [1]: the scaled pulse width $\sigma_z = l_e/N\lambda$, the resonator quality factor Q, the dimensionless electron beam current density j, and the desynchronism d. Simulations using FEL theory based on a self-consistent solution of the coupled Maxwell–Lorentz equations describe the evolution of the optical fields and investigate the character of the power oscillations. The results of these simulations show that some limit-cycle effects are common to changes in each of the dependent variables. In general, the frequency of the oscillations in the stable region of the limit cycle is dependent only on the desynchronism d. Limit-cycle behavior does not begin until the combination of Q, σ_z, d and j results in optical field amplitudes large enough to trap particles ($|a| > \pi$).

Once the limit cycle has started, the modulation amplitude relative to the average power increases rapidly and then stabilizes. As any one variable (except j) is increased further the oscillations pass through a quasiperiodic region marked by unstable sidebands into a region of stable sidebands and stable power with relatively small oscillations.

Fig. 1 shows the results of the simulations with $Q = 30$, $j = 2.5$, $d = 0.01$ and varying the pulse length σ_z. The solid line shows the modulation amplitude relative to the average power, and the dotted line shows the modulation frequency. For $\sigma_z \lesssim 1.0$, there is poor coupling between the electron and optical pulses resulting in low field strength, no trapped particles, and no limit-cycle behavior. When the pulse length becomes comparable to the slippage distance, the coupling between the optical and electron pulses is sufficient to create the strong fields required to cause the trapped particles and limit-cycle oscillations. As σ_z is increased further, the size of the subpulse relative to the size of the main pulse decreases. The fluctuations in the area of the main optical pulse due to the smaller subpulse decrease. This results in smaller amplitude oscillations of the power relative to the average power at steady-state. The frequency of the oscillations remains essentially constant throughout this range. As the pulse length be-

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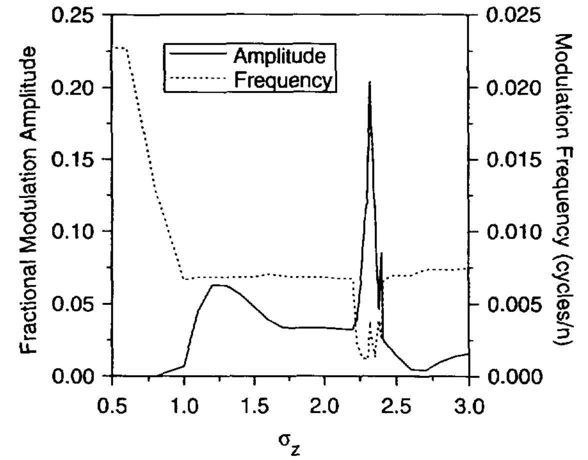

Fig. 1. Fractional modulation amplitude and modulation frequency vs. σ_z with $Q = 30$, $j = 2.5$, and $d = 0.01$.

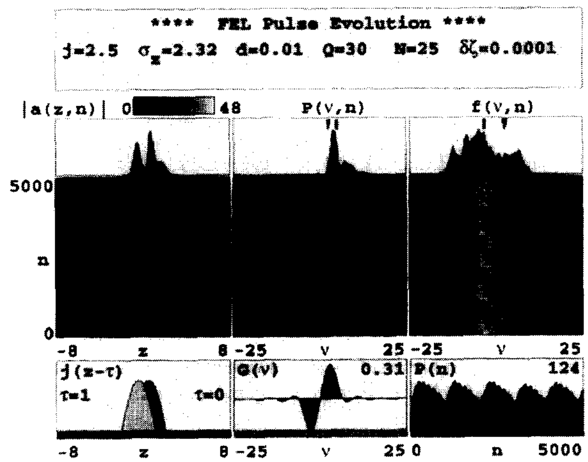

Fig. 2. Longitudinal multimode simulation at peak modulation amplitude.

comes longer than approximately 2.2 slippage distances, $\sigma_z \approx 2.2$, the character of the modulation changes. The fractional amplitude of the modulation rises rapidly and the frequency of the modulation decreases. At $\sigma_z \approx 2.5$, the fractional amplitude returns to a more moderate value and the frequency returns to the previous value. The number of data points taken between the range $\sigma_z \approx 2.2$ to $\sigma_z \approx 2.5$ was increased for a more detailed analysis of the limit-cycle effects in this region.

Fig. 2 is a simulation at the peak modulation amplitude where $\sigma_z \approx 2.32$. The upper plots show the evolution of the optical field amplitude $|a(z,n)|$, where z is the longitudinal position and n is the pass number. Also plotted is the evolution of the optical power spectrum $P(\nu, n)$ and the electron phase velocity spectrum $f(\nu, n)$, where ν is the phase velocity [1]. The three plots across the bottom of Fig. 2 are the electron pulse current $j(z)$ shown at the beginning ($\tau = 0$) and end ($\tau = 1$) of the undulator, the weak-field, single-mode gain spectrum $G(\nu)$, and the dimensionless power evolution $P(n)$. On the optical field amplitude plot, the subpulses are seen to form and move forward, which results in the limit-cycle oscillations in the power. The position in z at which the subpulses form oscillates with respect to n. Some subpulses start more forward in z than others resulting in a smaller optical subpulse. The oscillation in optical subpulse size results in larger oscillations in the size of the main optical pulse and in larger oscillations of the integrated power $P(n)$.

Acknowledgements

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